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EFFECT OF PHYSICAL TRAINING ON
BLOOD VOLUME, HEMOGLOBIN, ALKALI
RESERVE AND OSMOTIC RESISTANCE
OF ERYTHROCYTES

A DISSERTATION SUBMITTED TO THE FACULTY
OF THE DIVISION OF THE BIOLOGICAL
SCIENCES IN CANDIDACY FOR THE DEGREE
OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF PHYSIOLOGY

1936

By
JOHN EMERSON DAVIS

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EFFECT OF PHYSICAL TRAINING ON BLOOD VOLUME,
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RESISTANCE OF ERYTHROCYTES

That previously confined dogs, when exercised on treadmills for a few days, undergo a loss of blood volume, erythrocytes, and hemoglobin has been shown by Broun (1,2). This destruction he attributes to a process of mechanical fragmentation of cells which was earlier advocated by Rous and Robertson (3) as a normal mode of blood destruction. McMaster, Broun, and Rous, (4) using biliary fistula dogs, showed that an increased bilirubin output accompanied hemoglobin reduction during a few days of treadmill exercise. Thörner (5,6) has reported an increased osmotic resistance of erythrocytes in man and dog after physical training. Hastings (7) has shown that in vivo hemolysis occurs in the serum of untrained dogs after exercise. Broun's dogs showed recovery of erythrocytes and hemoglobin with continued exercise, and of blood volume after three weeks rest. Anemic anoxemia has been suggested by Steinhaus (8) as the bone marrow stimulant in this recovery process. He attributes the high erythrocyte osmotic resistance of Thörner's trained dogs to a weeding out of older, less resistant corpuscles by the fragmentation process which is augmented by the higher circulatory rates of exercise.

The present work was undertaken to determine whether or not prolonged physical training will induce an increase of blood volume and erythrocytes, and if possible, to shed light on the stimulus to blood formation and the mode of blood destruction in exercise.

Procedure.- Five dogs were confined for two to three months without exercise. During this period and throughout the training and post-training periods that followed, the dogs were fed daily a constant mixed diet of 200 gm. beef lungs, 200 gm. of beef liver, and 200 gm. bread. Two dogs were exercised by swimming for two hours daily in water at 30° C.; and three dogs were made to run on a treadmill on 25 per cent grade for a distance of six miles daily. The exercise periods varied in length from four to nine weeks, and post-exercise observations were continued for four to six weeks thereafter. The two forms of exercise were adopted to cover possible effects on the blood and of pH variations, which according to Rice and Steinhaus (9) varies with the body temperature. Rectal temperatures in our dogs were increased by about 1° C. after running, and decreased about 2° C. after swimming.

Dogs were fed during the training period at the conclusion of the daily exercise. All blood determinations were made under basal conditions of the animal at least eighteen hours after previous exercise and food. The following blood determinations were made: Blood volume by the carbon monoxide inhalation method of Chang and Harrop (10), using the blood gas analysis technique of Van Slyke and Neill (11); hemoglobin per unit volume of blood by Palmer's (12) method; blood cell volume by hematocrit; red corpuscle counts; erythrocyte osmotic resistance by Hasting's (7) method; and plasma bicarbonate calculated from the Henderson-Hasselbalch equation from the total CO₂ by Van Slyke and Neill (11) method, and from the pH by the method of Hastings and Sendroy (13).

RESULTS

1. Blood volume is markedly decreased in the first week of exercise in three of the four dogs (Fig. 1). Two recovered during the next two weeks of continued exercise, while one (Dog 3, a swimmer) recovered at the end of four weeks of continued exercise. All dogs, after six weeks of exercise, showed a blood volume higher than normal, which persisted throughout the exercise period and for one to five weeks thereafter.

2. Total cell volume is reduced in all dogs during the first week of training (Fig. 2). The two running dogs showed recovery to normal in the third week of exercise, while the swimmers required five weeks. During the remainder of the period, the two swimmers and one runner showed marked supra-normal cell volume which persisted for four weeks after cessation of exercise, at which time we discontinued observations.

3. Erythrocyte number.— All dogs showed a decreased erythrocyte number during the first week of exercise (Fig. 4). An erythrocyte count above the normal was observed in each dog after the initial fall, and the polycythemia persisted throughout the exercise period and for four weeks after the cessation of exercise.

4. Hemoglobin per unit volume of blood is significantly lowered in all four dogs during the first week's exercise, and recovers irregularly, but in no case exceeds appreciably the normal level (Fig. 3). In Table VI, the weight of hemoglobin per corpuscle is seen to decrease with exercise. This is in accord with work reported by Thörner.

5. Total circulating hemoglobin.— The total circulating hemoglobin of the body is increased significantly by five to seven weeks of exercise (Table VII). Because of the fact that the

polycytemias and high blood volumes in our trained dogs usually persisted for four weeks or longer after cessation of exercise, we are led to believe that the "oxygen debt" of exercise is the stimulus to blood formation (in exercise). Presumably an anoxemia based on anemia would cease to operate as soon as the normal oxygen capacity of the blood has been restored. Some of the members of the 1921 Expedition into the Peruvian Andes (Barcroft et al) (15) showed a prompt (2 weeks) return to normal of erythrocyte counts upon descending to lower altitudes. These subjects had shown significant polycytemias at high altitudes and these polycytemias were caused by a condition comparable to anemia with respect to arterial oxygen supply.

6. Alkali reserve.-- In both running and swimming dogs, exercise finally induces a supra-normal alkali reserve, although in two dogs the elevation is preceded by a reduction during the early stages of training (Fig. 5). The two dogs showing the initial reduction appeared, before training, to be healthier dogs. Walinski (14) has reported increased alkali reserve in man after physical training, but an increase in alkali reserve in trained dogs has not, to our knowledge, been reported previously. Exercise, it seems, "chemically trains" the blood by increasing its content of available base for the neutralization of acids. It is well known that during exercise CO_2 , lactic and other acids are formed in the muscles. Carbon dioxide at all times and lactic acid sometimes appears in the blood during exercise. Since these substances must be buffered, their very presence in excess in blood may induce the formation of a greater alkali reserve.

7. Erythrocyte osmotic resistance increases significantly with training in the two swimming dogs, but decreases slightly in Dog 5, a runner. One of the swimming dogs failed to show an

increased cell resistance during the first week of exercise but he also failed to show a significant reduction of hemoglobin during that time (Dog 4, Figs. 3 and 6). Dog 5 showed a decreased cell resistance in the first week of exercise, accompanied by a reduction of 15 per cent in hemoglobin per unit volume of blood. It will be noticed that changes in osmotic resistance of corpuscles occur simultaneously with reduction in hemoglobin per unit volume of blood. (Hemoglobin of Dog 5 does not appear in the tables.) Since only our swimming dogs showed increased osmotic resistance of erythrocytes during the exercise period, we suggest that this may have been caused by the slightly reduced (by 2° C.) body temperature, which we observed in them immediately after swimming.

SUMMARY

The following changes in dog's blood due to a period of physical exercise are reported:

1. During the first week of exercise, a reduction of blood volume, cell volume, erythrocyte number, and hemoglobin per unit volume of blood occurred.
2. During the period of exercise, the blood volume, the total cell volume, and the erythrocyte count, not only returned to normal, but exceeded the normal. The hemoglobin per unit volume of blood returned to normal, but did not exceed the normal, although exercise finally induced an increase in the total circulating hemoglobin. A decreased weight of hemoglobin per corpuscle was observed throughout the exercise period.
3. An increase of alkali reserve in both running and swimming dogs occurred.
4. A significant increase of erythrocyte osmotic resistance occurred in two swimming dogs, but a slight

decrease of resistance occurred in one running dog. It is suggested that body temperature may be a factor in causing erythrocyte osmotic resistance changes.

Since the polycytemia and supra-normal blood volume persisted for about four weeks after the cessation of exercise, it is concluded that the oxygen debt of exercise is the stimulus to the increased blood formation during exercise.

TABLE I
THE EFFECT OF EXERCISE ON THE BLOOD
Dog No. 1-Weight 18.3 Kg.

Date	Blood Volume	Blood Cell Volume	Hemo- globin Oxygen Cap.	Erythrocyte Count	Plasma Bicar- bonate
Controls: Pre-exercise Period					
July 23	1742cc.	697cc.	25.2		
July 30	1760	715	27.9	7,105,000	
Aug. 7	2002	712	26.4	7,075,000	20.32 mM/L
Average	1835	708	26.5	7,090,000	20.32
Aug. 8	Exercise commenced. Treadmill Running.				
6 days exercise	1613	532	23.0	7,000,000	
11 " "					16.93 mM/L
20 " "	1902	704	23.0	6,810,000	
31 " "	1920	735	25.4	6,970,000	
40 " "					20.58 mM/L
47 " "	2142	714	26.4	7,620,000	
64 " "	2288	769	25.1	7,650,000	23.25 mM/L
Oct. 16	Exercise Discontinued.				
After 18 days rest	Post-exercise Period				19.22 mM/L
" 27 " "	2264	769		7,420,000	19.50 mM/L
" 41 " "	1821	650		6,830,000	

TABLE II
THE EFFECT OF EXERCISE ON THE BLOOD

Dog No. 2-Weight 26.5 Kg.

Date	Blood Volume	Blood Cell Volume	Hemo- globin Oxygen Cap.	Erythrocyte Count	Plasma Bicar- bonate
Controls: Pre-exercise Period					
July 5	2723	1035	25.4	6,450,000	
July 24	2812	984	25.7	6,880,000	
Aug. 13	2812	1054	25.9	6,669,000	17.76 mM/L
Average	2782	1024	25.7	6,666,000	17.76 mM/L
Aug. 19 Exercise Commenced (Treadmill)					
6 days exercise	2808	887	18.6	6,150,000	
18 " "	2852	1011	24.8	6,190,000	18.44 mM/L
31 " "	3214	1012	25.2	6,915,000	19.70
53 " "	2960	1018		6,650,000	23.09
Oct. 12 Exercise Discontinued					
After 18 days rest					19.80 mM/L
" 28 " "	2980	993		6,910	
" 43 " "	2777	972		6,710	19.42 mM/L

TABLE III
THE EFFECT OF EXERCISE ON THE BLOOD
Dog No. 3-Weight 18.0 Kg.

Date	Blood Volume	Blood Cell Volume	Hemo- globin Oxygen Cap.	Erythrocyte Count	Plasma Bicar- bonate
Controls: Pre-exercise Period					
Oct. 31	2343	757			19.94 mM/L
Nov. 19	2383	782	20.6	6,580,000	
Nov. 28			20.6	6,950,000	
Dec. 3			20.4		
Dec. 5	2382	793	20.6	6,970,000	19.71 mM/L
Average	2370	777	20.6	6,830,000	19.82 mM/L
Dec. 11 Exercise Commenced (Swimming)					
After 6 days exer.	2027	681	18.3	6,780,000	18.27 mM/L
" 13 " "	2070	690	19.4		
" 20 " "			21.0	7,350,000	
" 28 " "			20.4	7,395,000	
" 35 " "	2359	786	20.4	6,100,000	
" 42 " "	2559	853	20.4	7,150,000	
" 49 " "	2450	857	20.8	7,210,000	21.30 mM/L
Jan. 30 Exercise Discontinued					
After 14 days rest	2115	803	20.0		19.70 mM/L
" 28 " "	2344	812	20.0	6,840,000	20.05 mM/L

TABLE IV
THE EFFECT OF EXERCISE ON THE BLOOD
Dog No. 4-Weight 12.1 Kg.

Date	Blood Volume	Blood Cell Volume	Hemo- globin Oxygen Cap.	Erythrocyte Count	Plasma Bicar- bonate
Control Period (Pre-exercise)					
Oct. 29				5,980,000	18.27 mM/L
Nov. 6					17.77 mM/L
Nov. 19	1795	488	20.0		
Nov. 26	1748	494	20.0	6,000,000	
Nov. 28	1805	505	20.0	6,130,000	
Dec. 3	1751	496	20.0		18.30 mM/L
Dec. 11	Exercise Commenced (Swimming)				
After 6 days exer.	1652	467	15.4	5,790,000	21.90 mM/L
" 13 "	1748	414	15.4	5,000,000	
" 20 "			16.7	5,340,000	
" 28 "			17.1	5,730,000	
" 35 "	1851	531	18.3		21.68 mM/L
" 42 "	2007	621	18.7	6,830,000	
" 49 "	1872	636	19.2	6,930,000	
Jan. 30	Exercise Discontinued				
After 14 days rest	1727	569	20.0	6,510,000	21.35 mM/L
" 28 "	1861	558	20.0		21.00 mM/L

TABLE V
OSMOTIC RESISTANCE OF ERYTHROCYTES
CONCENTRATIONS OF SODIUM CHLORIDE IN WHICH 50 PER CENT
OF THE HEMOGLOBIN IS LAKED

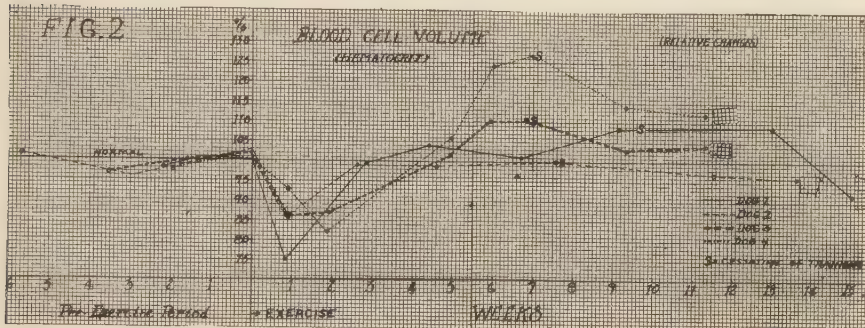
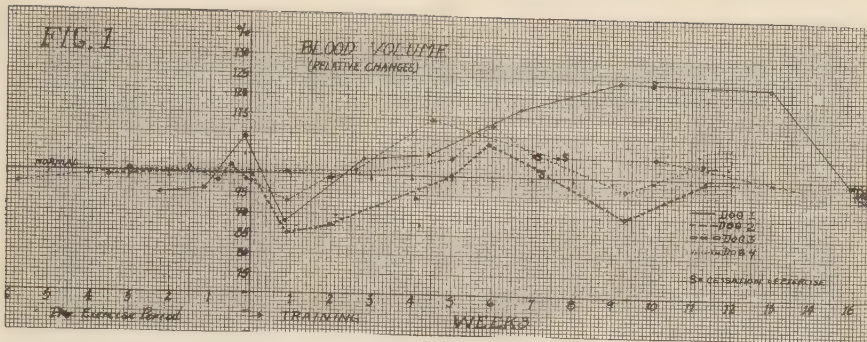
Time of Determination	Dog No. 5	Dog No. 4	Dog No. 3	
23 days before exercise	.427%			
20 " " "	.424			
15 " " "	.432	.432%	.456%	
11 " " "	.434	.432	.462	
9 " " "	.430		.458	
6 " " "	.434			
3 " " "	.432			
Pre-exercise average	.430%	.432%	.458%	
After 6 days exercise		.433%	.440%	
" 13 " "	.440%	.400		
" 16 " "	.444			
" 20 " "	.443	.415	.440	
" 27 " "	.440		.443	
" 36 " "		.411	.444	
" 41 " "		.397	.447	
" 48 " "		.400	.444	
Exercise average	.442%	.405%	.443%	
28 days after cessation exercise		.415%	.456%	
38 days " " "		.415	.455	
Post-exercise average		.415%	.455%	

TABLE VI
EFFECT OF EXERCISE ON THE WEIGHT OF
HEMOGLOBIN PER CORPUSCLE
(gm. X 10^{-12})

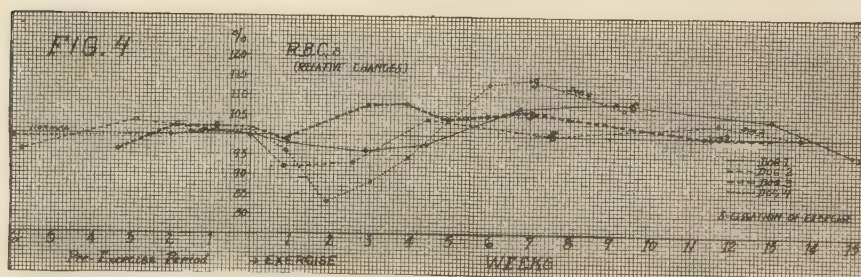
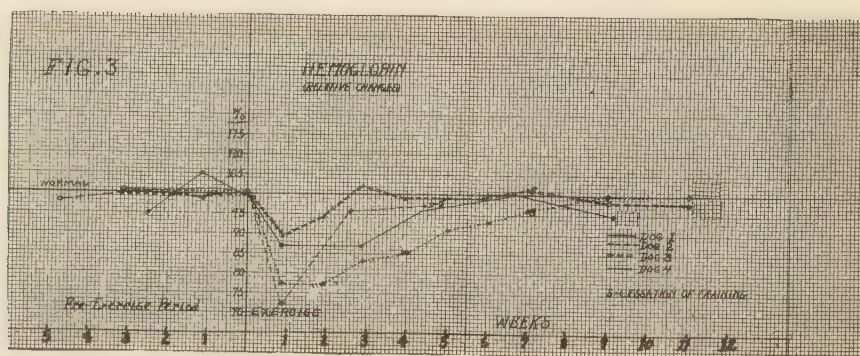
	Dog No. 1	Dog No. 2	Dog No. 3	Dog No. 4
Pre-exercise normal	28.0	29.0	22.6	24.8
After 1 week of exercise	24.6	22.6	20.2	19.9
After 7 weeks of exercise	26.0		21.6	20.8

TABLE VII
EFFECT OF EXERCISE ON TOTAL CIRCULATING HEMOGLOBIN

	Dog No. 1	Dog No. 2	Dog No. 3	Dog No. 4
Pre-exercise normal	100%	100%	100%	100%
After 1 week of exercise	76	73	76	72
After 5 weeks of exercise		113		
After 6 weeks of exercise			107	106
After 7 weeks of exercise	124			



Figs. 1 and 2.— Relative changes in blood volume and blood cell volume of dogs during a period of physical training. S = end of training period.



Figures 3 and 4.- Relative changes in hemoglobin per unit volume of blood, and erythrocyte count in dogs during a period of physical training. S = end of training period.

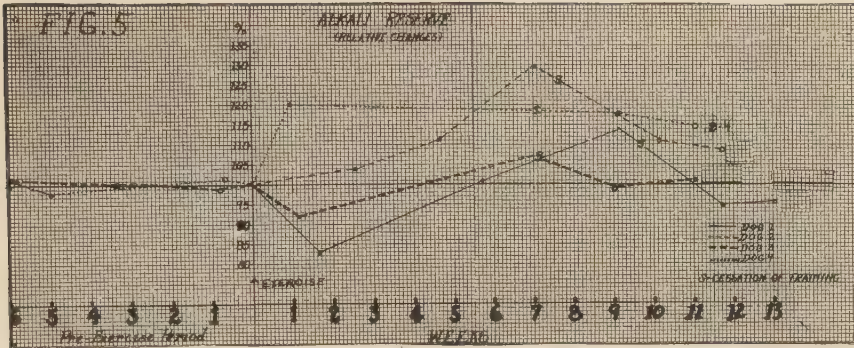


Fig. 5.- Relative changes in alkali reserve of dogs' blood during a period of physical training. S = end of training period.

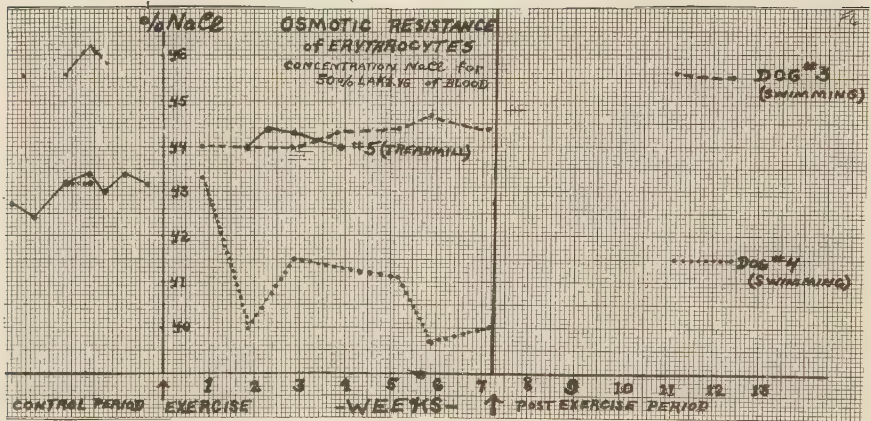


Fig. 6.- Relative changes in erythrocyte osmotic resistance of dogs' blood during a period of physical training.

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